

CLAIMS

What is claimed is:

1 1. A method of timing recovery of symbols in a received signal, comprising the steps
2 of:

3 (a) generating a sequence of samples from the received signal with a sample period and
4 sample phase related to a symbol rate of the symbols;

5 (b) generating a phase error for a current sample from the sequence based on a gradient of
6 a blind cost criterion of Bussgang-class cost functions;

7 (c) adjusting at least one of the sample period and sample phase based on the phase error
8 such that a magnitude of the phase error is driven to a predetermined point; and

9 (d) repeating steps (a), (b), and (c) for subsequent samples.

1 2. The invention as recited in claim 1, wherein step (b) comprises the steps of:

2 (b1) calculating a blind cost error term based on the sample;

3 (b2) forming an approximation of a derivative of the received signal with respect to the
4 sampling phase; and

5 (b3) combining the blind cost error term and the approximation to form the phase error.

1 3. The invention as recited in claim 1, wherein step (b) comprises the steps of:

2 (b1) calculating a blind cost error term based on the sample; and

3 (b2) forming an approximation of a derivative of the received signal with respect to the
4 sampling phase.

1 4. The invention as recited in claim 3, further comprising the steps of (e) generating
2 a quality measure for the received signal from the sequence; and wherein step (b1) further
3 comprises the step of generating at least one other cost function error term based on a
4 corresponding cost function criterion.

1 5. The invention as recited in claim 4, further comprising the steps of:

2 b3) selecting an error value, based on the quality measure, as either the blind cost error
3 term or one cost function error term; and

4 b4) combining the error value with the approximation to form the phase error.

1 6. The invention as recited in claim 4, further comprising the steps of:

2 b3) selecting an error value, based on the quality level, as a weighted combination of the
3 blind cost error term and the at least one other cost error term as the error value; and

4 b4) combining the error value with the approximation to form the phase error.

1 7. The invention as recited in claim 4, wherein, for step (b) the at least one cost
2 function error term includes a least mean squares error term.

1 8. The invention as recited in claim 4, wherein, for step (b) the quality measure is
2 based on at least one of a signal-to-noise ratio (SNR) of the received signal, SNR of a trellis
3 decoder employed to detect each symbol, a number of symbols received, errors within a number
4 of symbols received and detected, and vestigial sideband signal (VSB) framelock.

1 9. The invention as recited in claim 3, wherein, for step (b), either i) the blind cost
2 criterion is a Constant Modulus (CM) cost criterion and the gradient is the CM algorithm or ii)
3 the blind cost criterion is a Single-axis Constant Modulus (SA-CM) criterion and the gradient is a
4 SA-CM algorithm.

1 10. The invention as recited in claim 9, wherein, for step (b) the CM cost criterion J_{CM}
2 is expressed as:

$$3 \quad J_{CM} = E[(\rho^2 - |y_n(\tau)|^2)^2],$$

4 wherein ρ^2 is a dispersion constant, $y_n(\tau)$ is a discrete value representing the current
5 sample generated at the sampling period, and τ represents the sampling phase; and

6 wherein the gradient is $dJ_{CM}/d\tau$ and is expressed as:

$$7 \quad dJ_{CM}/d\tau = (dJ_{CM}/dy_n(\tau))dy_n(\tau)/d\tau,$$

8 wherein the derivative of the signal with respect to the sampling phase is $dy_n(\tau)/d\tau$ and a
9 derivative of J_{CM} with respect to $y_n(\tau)$ is the blind cost error term determined as:

10 $y_n(\tau)(\rho^2 - |y_n(\tau)|^2)$.

1 11. The invention as recited in claim 1, wherein, for step (b), the phase error is
2 generated in accordance with a phase error calculation derived for a cost function error criterion
3 having a corresponding cost function error term, the phase error calculation substituting the blind
4 cost error term for the cost function error term.

1 12. The invention as recited in claim 11, for step (b) comprises the steps of:

2 (b1) calculating a blind cost error term for a current sample $y_n(\tau)$ and a blind cost error
3 term for a previous sample $y_{n-1}(\tau)$, based on a gradient of a constant modulus (CM) cost criterion;
4 and

5 (b2) combining the current and previous blind cost error terms with the current and
6 previous samples generated at the sampling period to generate the timing phase error as:

7 $y_n(\tau)y_{n-1}(\tau) ((\rho^2 - |y_n(\tau)|^2) - (\rho^2 - |y_{n-1}(\tau)|^2))$

8 where ρ^2 is a dispersion constant and τ represents the sampling phase.

1 13. The invention as recited in claim 1, wherein, for step (a) the received signal is
2 demodulated from either a m -ary quadrature amplitude modulated (QAM) signal, a m -ary offset
3 QAM signal, an m -ary phase-shift keyed modulated (m -ary PSK) signal, a vestigial sideband
4 modulated (VSB) signal, a pulse amplitude modulated (PAM) signal, a signal modulated in
5 accordance with a CCITT 802.11 standard, or a signal modulated in accordance with a V.27
6 standard.

1 14. The invention as recited in claim 1, wherein, for step (b), the Bussgang-class cost
2 function is selected from either a Godard cost function, Benverniste-Goursat-Ruget cost function,
3 or a Sato cost function.

1 15. The invention as recited in claim 1, wherein the method is embodied in a
2 processor of an integrated circuit.

1 16. The invention as recited in claim 15, wherein the integrated circuit is embodied in
2 a demodulator of a high definition television signal.

1 17. The invention as recited in claim 1, wherein, for step (a), the received signal is a

2 vestigial sideband (VSB) modulated signal, and, for step (b) the blind cost criterion is a Single-
3 axis Constant Modulus (SA-CM) criterion and the gradient is a SA-CM algorithm.

1 18. The invention as recited in claim 1, wherein, for step (a), the received signal is a
2 digital television signal having data encoding and modulation in accordance with an ATSC
3 standard.

1 19. Apparatus for timing recovery of a symbol rate for symbols in a received signal,
2 comprising:

3 a timing reference providing a reference signal;

4 a sample generator configured to generate a sequence of samples from the received signal
5 with a sample period and sample phase based on the reference signal and related to the symbol
6 rate;

7 a blind cost error term generator configured to generate a blind cost error term for a
8 current sample of the sequence in accordance with a gradient of a blind cost criterion of
9 Bussgang-class cost functions; and

10 a timing phase detector configured to generate a phase error for the current sample from
11 the sequence and based on the blind cost error term;

12 wherein the timing reference modifies the reference signal based on the phase error to
13 adjust at least one of the sample period and sample phase such that a magnitude of the phase
14 error is driven to zero.

1 20. The invention as recited in claim 19, wherein the timing phase detector forms an
2 approximation of a derivative of the received signal with respect to the sampling phase; and
3 combines the blind cost error term and the approximation to form the phase error.

1 21. The invention as recited in claim 20, wherein the timing phase detector includes a
2 filter having a delay chain receiving the sequence and a combiner, and the combiner forms the
3 derivative of the signal with respect to the sampling phase by generating the difference between a
4 previous sample from a corresponding delay of the delay chain and the current sample.

1 22. The invention as recited in claim 20, wherein the blind cost criterion is the
2 Constant Modulus (CM) cost criterion and the gradient is the CM algorithm, and wherein the

3 blind cost error term is generated by:

4

5 ii) forming the gradient of the CM cost criterion as $dJ_{CM}/d\tau$ expressed as:

6
$$dJ_{CM}/d\tau = (dJ_{CM}/dy_n(\tau))dy_n(\tau)/d\tau,$$

7 wherein the CM cost criterion J_{CM} is defined as:

8
$$J_{CM} = E[(\rho^2 - |y_n(\tau)|^2)^2]$$

9 in which ρ^2 is a dispersion constant, $y_n(\tau)$ is a discrete value representing the current sample
10 generated at the sampling period, and τ represents the sampling phase; and

11 wherein the derivative of the received signal with respect to the sampling phase is

12 $dy_n(\tau)/d\tau$ and a derivative of J_{CM} with respect to $y_n(\tau)$ is the blind cost error term given by

13
$$y_n(\tau)(\rho^2 - |y_n(\tau)|^2).$$

1 23. The invention as recited in claim 19, wherein the phase detector generates the
2 phase error in accordance with a phase error calculation derived for a cost function error criterion
3 having a corresponding cost function error term, the phase error calculation substituting the blind
4 cost error term for the cost function error term.

1 24. The invention as recited in claim 23, wherein the blind-cost error term is based on
2 a gradient of a constant modulus (CM) cost criterion for the current sample defined as

3
$$dJ_{CM}/d\tau = (dJ_{CM}/dy_n(\tau))dy_n(\tau)/d\tau,$$

4 wherein $J_{CM} = E[(\rho^2 - |y_n(\tau)|^2)^2]$ is the CM cost criterion, ρ^2 is a dispersion constant, $y_n(\tau)$ is a
5 discrete value representing the current sample generated at the sampling period, τ represents the
6 sampling phase, and $dy_n(\tau)/d\tau$ is a derivative of the received signal with respect to the sampling
7 phase is $dy_n(\tau)/d\tau$, and a derivative of J_{CM} with respect to $y_n(\tau)$ is defined as the blind cost error
8 term $e_{CMA}[n]$ given by

9
$$e_{CMA}[n] = y_n(\tau)(\rho^2 - |y_n(\tau)|^2); \text{ and}$$

10 wherein the timing phase detector combines a current blind cost error term $e_{CMA}[n]$ and a
11 previous blind cost error term $e_{CMA}[n-1]$ with the current sample $y_n(\tau)$ and previous sample $y_{n-1}(\tau)$

12 to generate the timing phase error as:

13

$$y_n(\tau)y_{n-1}(\tau) ((\rho^2 - |y_n(\tau)|^2) - (\rho^2 - |y_{n-1}(\tau)|^2))$$

1 25. The invention as recited in claim 19, wherein the sample generator comprises an
2 analog-to-digital (A/D converter) configured to generate a sequence of discrete values from the
3 received signal.

1 26. The invention as recited in claim 25, wherein the timing reference is an oscillator
2 coupled to the A/D converter, and the A/D converter generates the sequence of discrete values so
3 as to convert the received signal to the sequence of samples with the sampling phase and the
4 sampling period.

1 27. The invention as recited in claim 25, wherein the sample generator further
2 comprises an interpolator coupled to the A/D converter and coupled to the timing reference
3 generator, wherein the interpolator is configured to adjust the sequence of discrete values from
4 the A/D converter to form the sequence of samples with the sampling period and the sampling
5 phase.

1 28. The invention as recited in claim 25, wherein the received signal is demodulated
2 from either a m -ary quadrature amplitude modulated (QAM) signal, a m -ary offset QAM signal,
3 an m -ary phase-shift keyed modulated (m -ary PSK) signal, a vestigial sideband modulated (VSB)
4 signal, a pulse amplitude modulated (PAM) signal, a signal modulated in accordance with a
5 CCITT 802.11 standard, or a signal modulated in accordance with a V.27 standard.

1 29. The invention as recited in claim 19, further comprising 1) a signal quality
2 processor generating a signal quality measure (SQM) signal, and 2) at least one cost function
3 error generator, each cost function error generator configured to generate a cost function error
4 term with a corresponding cost function criterion.

1 30. The invention as recited in claim 19, further comprising a multiplexer selecting
2 either the blind cost error term or at least one cost function error term based on the SQM signal;
3 and

4 wherein the timing phase detector, based on the SQM signal, either i) provides the phase
5 error generated with the blind cost error term or ii) provides the phase error based on the selected

6 cost function error term from the multiplexer.

1 31. The invention as recited in claim 29, further comprising a weighting mechanism
2 circuit, the weighting mechanism circuit forming, based on the SQM signal, a weighted
3 combination of i) the blind cost error term with ii) the at least one cost function error term, and
4 wherein the timing phase detector, based on the SQM signal, generates the phase error with the
5 weighted combination.

1 32. The invention as recited in claim 29, wherein the SQM signal is based on at least
2 one of a signal-to-noise ratio (SNR) of the received signal, SNR of a trellis decoder employed to
3 detect each symbol, a number of symbols received, errors within a number of symbols received
4 and detected, and ATSC frame synchronization acquisition.

1 33. The invention as recited in claim 19, wherein the blind cost error generator is
2 included in an adaptive equalizer, the blind cost error generator forming the blind cost error term
3 to update equalizer coefficients.

1 34. The invention as recited in claim 19, wherein the Bussgang-class cost function is
2 selected from either a Godard cost function, Benverniste-Goursat-Ruget cost function, or a Sato
3 cost function.

1 35. The invention as recited in claim 19, wherein the apparatus is embodied in an
2 integrated circuit.

1 36. The invention as recited in claim 35, wherein the apparatus is embodied in a
2 demodulator of a high definition television signal.

1 37. The invention as recited in claim 19, wherein the received signal is a vestigial
2 sideband (VSB) modulated signal, and the blind cost criterion is a Single-axis Constant Modulus
3 (SA-CM) criterion and the gradient is a SA-CM algorithm.

1 38. The invention as recited in claim 19, wherein the received signal is a digital
2 television signal having data encoding and modulation in accordance with an ATSC standard.

1 39. A computer-readable medium having stored thereon a plurality of instructions, the
2 plurality of instructions including instructions which, when executed by a processor, cause the

3 processor to implement a method for timing recovery of symbols in a received signal, the method
4 comprising the steps of:

5 (a) generating a sequence of samples from the received signal with a sample period and
6 sample phase related to a symbol rate of the symbols;

7 (b) generating a phase error for a current sample from the sequence based on a gradient of
8 a blind cost criterion of Bussgang-class cost functions;

9 (c) adjusting at least one of the sample period and sample phase based on the phase error
10 such that a magnitude of the phase error is driven to zero; and

11 (d) repeating steps (a), (b), and (c) for subsequent samples.

1 40. The invention as recited in claim 39, wherein step (b) comprises the steps of:

2 (b1) calculating a blind cost error term based on the sample;

3 (b2) forming an approximation of a derivative of the received signal with respect to the
4 sampling phase; and

5 (b3) combining the blind cost error term and the approximation to form the phase error.